The Diurnal Variation of Atlantic Ocean Tropical Cyclone Cloud Distribution Inferred from Geostationary Satellite Infrared Measurements

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ABSTRACT

Satellite-measured equivalent blackbody temperatures of Atlantic Ocean tropical cyclones are used to describe the associated convection and cloud patterns. Average equivalent blackbody temperatures were developed from 538 geostationary satellite observations of 23 tropical cyclones. The average values were stratified into tropical storm or hurricane intensity category, then normalized to local standard time and composited to provide a 24 h diurnal time series. The composited values represent the mean cloud top temperature within data rings around the tropical cyclone centers.

The cloud top temperatures when compared to a mean tropical atmosphere suggest that the mean top of the dense cloud canopy of hurricanes is near 10.6 km and extends horizontally to 321 km radius from the center. The mean top of the dense canopy of tropical storms is near 9.7 km and extends horizontally to 278 km from the center. The mean top of the deep convection near the center of hurricanes is near 13 km and in tropical storms is near 12 km. A Fourier series analysis of the 24 h time series shows diurnal and semidiurnal cloud patterns which are statistically significant at the 0.0005 and 0.01 levels, respectively. The cloud cycles are in phase with the convection and cloud activity found in tropical systems by other investigators.

1. Introduction

The geostationary and polar orbiting meteorological satellites are providing measurements from which highly useful information about the cloud distribution of tropical cyclones and their environment is obtained. The diurnal oscillation of the cloudiness of tropical cyclones in the Atlantic Ocean was reported by Browner *et al.* (1977) using Synchronous Meteorological Satellite (SMS-I and SMS-II) imagery and of typhoons in the western north Pacific Ocean by Muramatsu (1983) using Geostationary Meteorological Satellite (GMS) infrared measurements. The horizontal distribution of the temperature of cloud tops of Atlantic and western north Pacific Ocean tropical cyclones was shown by Gentry *et al.* (1980) using infrared measurements obtained with the polar orbiting Nimbus 3, 4 and 5 satellites.

New quantitative estimates of vertical and horizontal cloud distribution developed from geostationary satellite infrared measurements are given in this report. The results of the Fourier series analysis of the 24 h time series of the mean daily cloud patterns show statistically significant diurnal and semidiurnal cycles.

2. Data

A data set comprised of 4304 area-averaged equivalent blackbody temperatures (T_{BB}) was compiled from 538 satellite observations of 23 Atlantic Ocean tropical cyclones that occurred during 1974–79. The satellite observations consist of measurements made with the infrared channel (11.5 μm) of the Visible and Infrared Spin Scan Radiometer (VISSR) of the Geostationary Operational Environmental Satellite (GOES).

A set of eight average T_{BB} values was developed from each of the satellite observations. Each average T_{BB} value represents the mean of all of the data points within a specific data region associated with each tropical cyclone. The data regions are delineated as concentric bands (annuli), 111 km (1° lat) wide, surrounding the tropical cyclone center. Eight contiguous, concentric bands, or data rings, are used and provide areal coverage to 888 km radius from the tropical cyclone centers. Only observations of tropical cyclones centered $\geqslant$ 111 km from land are included in the data set. In Fig. 1, a grid superimposed upon a satellite image of Hurricane Ella shows the common

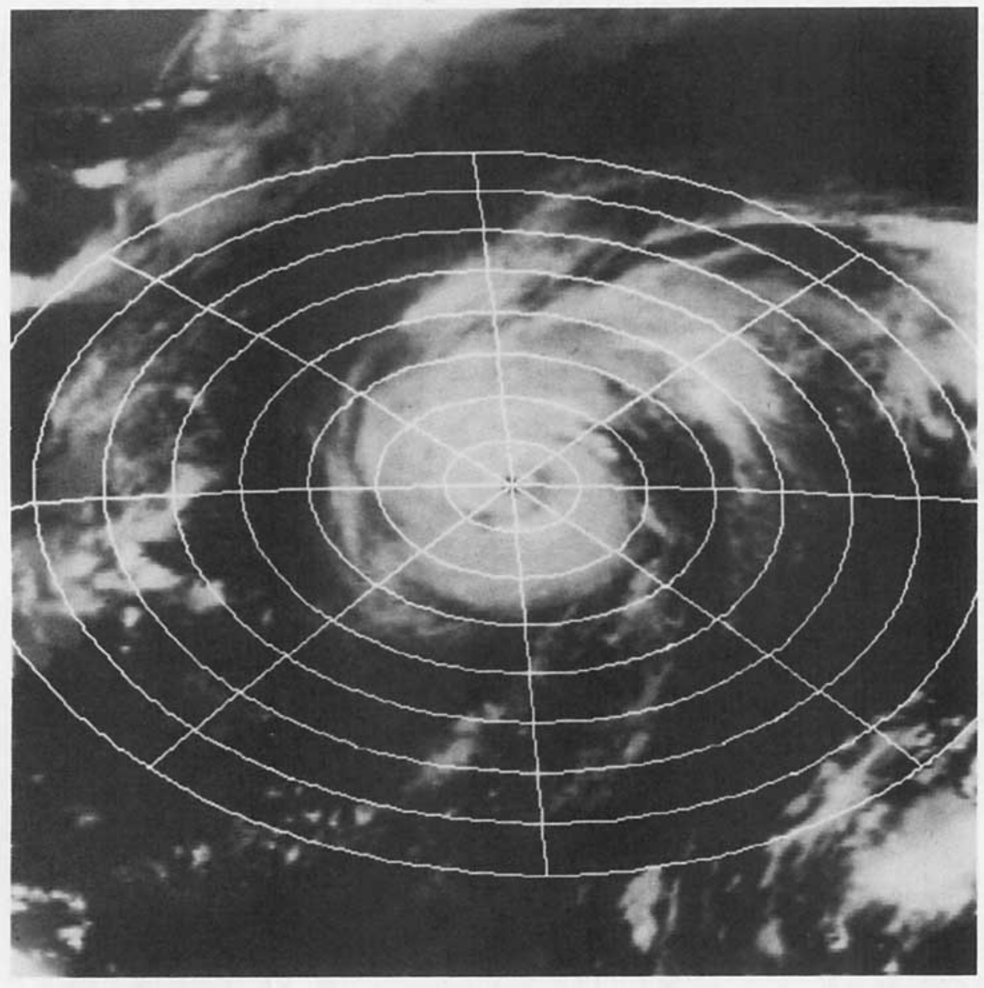

FIG. 1. Grid superimposed on a satellite image of Hurricane Ella.

disposition of the data rings with respect to the tropical cyclone centers. The average T_{BB} compilation was made using the Atmospheric and Oceanographic Information Processing System (AOIPS) at Goddard Space Flight Center.

At the observation times when coincidental areal coverage was available from the two GOES satellites that made the measurements, the T_{BB} values were compared for consistency and found to be near the same magnitude ($\leqslant 1$ K) over a broad range of the threshold. The T_{BB} measurements within clear sky regions over oceans compared favorably ($\leqslant 2$ K difference) with sea surface temperatures. Sea surface temperatures were obtained from National Weather Service sea surface analysis charts and from ship reports shown on daily weather charts.

The average T_{BB} values represent observations at various times of the day. These were composited to obtain a single mean T_{BB} for each hour of the day for each data ring. In compositing, the values were stratified by intensity category: 1) tropical storm (V = maximum wind at time of satellite observation < 65 kt) or 2) hurricane ($V \geqslant 65$ kt). Maximum winds of the tropical cyclones were obtained from the best track records prepared by the National Hurricane Center. Next, the average T_{BB} values were normalized to local standard time (LST) and finally a mean T_{BB} was computed for each hour of the day for each data ring using the accumulated averages. A low-pass filter (3 h running mean) was applied to reduce the hour-to-hour variability that may have resulted from an inequality in the number of observations included in each mean. This also smoothed the high-frequency oscillations. There are an average of 11 observations included in each unfiltered mean T_{BB} value.

The mean T_{BB} values were developed to be used to infer the horizontal and vertical distribution of clouds. The mean T_{BB} values near the tropical cyclone centers, where dense areal cloud cover is present, adequately represent cloud top temperatures. These temperatures, when compared to a standard tropical atmosphere, are used to make estimates of the level of the cloud top heights. The cloud top T_{BB} has been widely used to provide estimates of cloud top height. Heymsfield *et al.* (1983), however, in studies of the cirrus at and above the anvil top of thunderstorms has shown that the cloud top T_{BB} was as much as 10 K warmer than the environmental temperature. The estimates provided subsequently in this study may underestimate the true cloud top height.

The edge of the central dense overcast (CDO) is considered to be near a mean T_{BB} of 257 K. In a midwestern United States tropospheric atmosphere ~3 K colder than a rainy season tropical atmosphere, Adler and Fenn (1979) found a temperature of 257 K to be associated with the edge of the dense anvil cirrus of thunderstorms. While the midwestern United States atmosphere is not as exacting as desired for this tropical study, the case reported provides useful guidance for estimates made in conditions where strong convection and spreading high-level cloudiness associated with subsidence is found. Surrounding the CDO, partly cloudy skies exist, and the mean T_{BB} for this region represents a mixture of cloud top and earth surface temperatures. In this latter region, the mean T_{BB} may be compared with the high T_{BB} (>295 K) observed over water in clear sky regions to gain a qualitative estimate of cloud cover (i.e., mean T_{BB} greatly depressed from 295 K suggests there is abundant, or higher level, cloudiness present and, conversely, mean T_{BB} only slightly depressed from 295 K suggests there is less, or lower level, cloudiness present). Within the partly cloudy region, a portion of the observational scene was sometimes found over land. This varied from 4% of all observations at a radius of 111–222 km during which 22% of the observational scene was over land to 30% of all observations at a radius of 777–888 km during which 26% of the observational scene was over land. In a test made with the 45 observations from the 777–888 km data ring from one storm only, it was found that the removal of the measurements reduced the mean T_{BB} of the data ring by an average of 1.3 K. The mean T_{BB} over the land area was composited and showed a diurnal pattern with only a single maximum and minimum, but which is opposite to the diurnal pattern over the ocean (i.e., maximum mean T_{BB} occurred over land during the late afternoon, whereas a mean T_{BB} minimum occurred over the ocean). Additionally, the oceanic area mean T_{BB} showed a diurnal pattern with two maxima and two minima. The temporal pattern of the mean T_{BB} of the data ring was not significantly affected with the removal of the T_{BB} values measured over land. The results of this test suggest that the inclusion of the land area in the mean T_{BB} measurements of the data ring does not significantly alter the mean T_{BB} which are observed over the ocean at a radius of 777–888 km. Any impact attributed to the land measurements is even further reduced as the tropical cyclone center

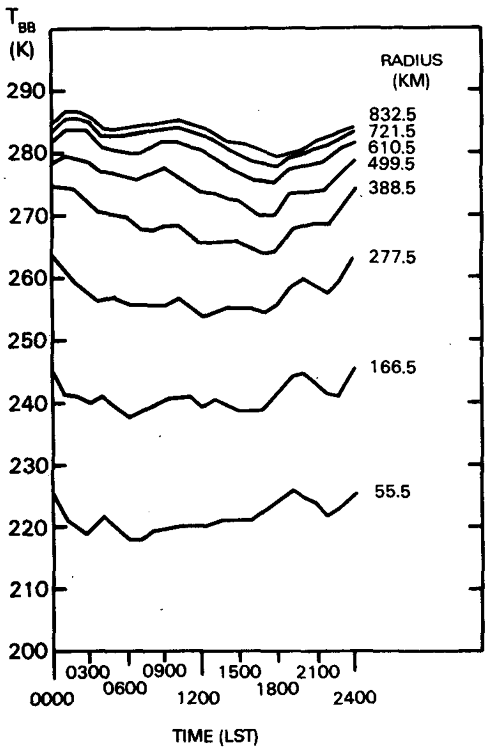

FIG. 2. Diurnal mean T_{BB} distribution of Atlantic Ocean tropical storms. Mean radius of the data from storm center is given in the right margin.

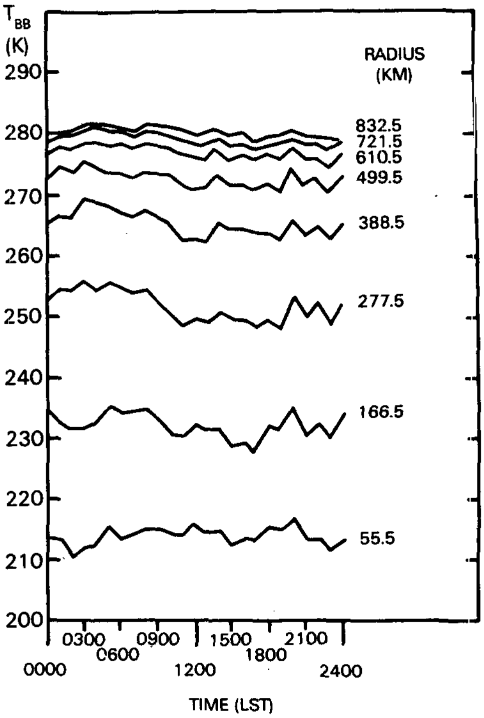

FIG. 3. As in Fig. 2 but for hurricanes.

is approached, since fewer observations (4% at radius of 111–222 km) extend over land.

3. Results

The filtered mean T_{BB} values for the tropical storms and hurricanes are shown plotted sequentially in Figs. 2 and 3, respectively. The curves represent the vertical and horizontal distribution of the cloud top temperatures as a function of distance and time. To aid in the interpretation, a Fourier series analysis (Panofsky and Brier, 1965) was made with each of the 24 h time series at each radius. A plot of the first and second harmonics obtained from the analysis is shown in Figs. 4 and 5 for the tropical storms and hurricanes, respectively. The statistical results of this analysis are shown in Tables 1 and 2.

From the information shown by Figs. 2 and 3 and Tables 1 and 2, several prominent cloud characteristics are readily noted and quantitative estimates can be made by applying the grand mean T_{BB} values (mean obtained using data from all of the storms) to a tropical atmosphere (Caribbean rainy season; Riehl, 1954). These features are:

1) The strongest convection (lowest grand mean T_{BB}) occurs near the tropical cyclone centers (55.5 km radius). The convection is more intense (colder grand mean T_{BB}) in the hurricanes than in the tropical storms and reaches vertically to 13 and 12 km, respectively. The standard deviation of the grand mean T_{BB} suggests that these cloud tops range from 12.8 to 13.2 km diurnally in hurricanes and 11.7 to 12.3 km in tropical storms.

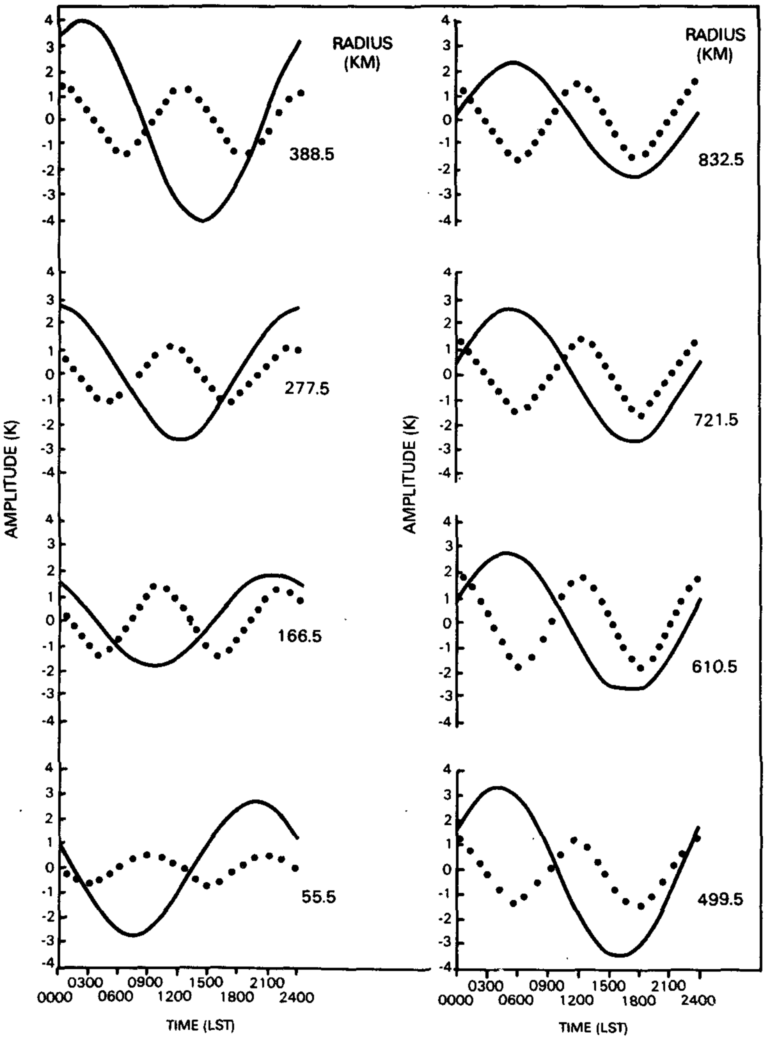

FIG. 4. First (solid) and second (dotted) harmonics of the diurnal mean T_{BB} distribution of Atlantic Ocean tropical storms. Amplitude (K) of the harmonic is given in left margin. Mean radius of data from storm center is given in the right margin.

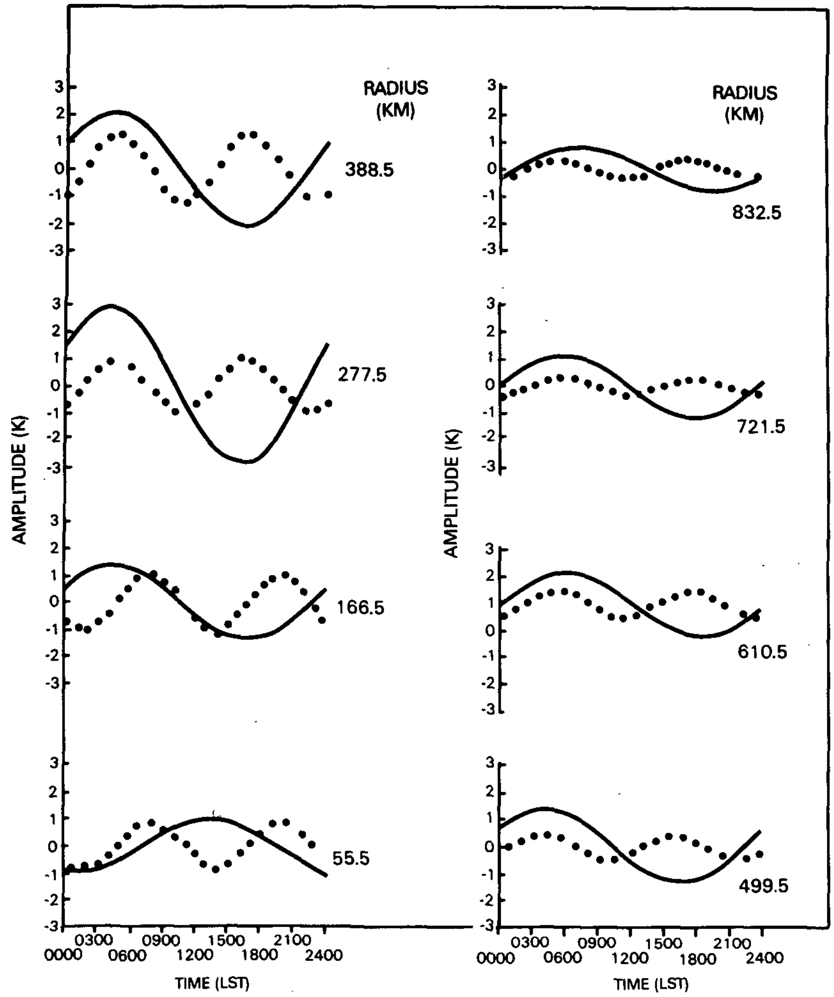

FIG. 5. As in Fig. 4 but for hurricanes.

2) The mean cloud top height of the central dense canopy of hurricanes is near 10.6 km and near 9.7 km in tropical storms. This is obtained using the mean of the T_{BB} within 333 km of the centers.

3) The mean edge of the central dense overcast (CDO) is located near 321 km radius from the center of hurricanes and 277.5 km radius from the center of tropical storms. These distances were determined with the linear interpolation of the distance from center of the grand mean T_{BB} of 257 K (this value represents the edge of the CDO).

4) The mean cloud top height at the edge of the CDO is near 7.4 km.

More specific cloud characteristics are noted with the results of the Fourier series analysis of the time series (Tables 1 and 2). This analysis describes the variability and periodicity of the oscillations of the mean T_{BB} throughout the day. The first ten harmonics of the time series were analyzed but the results of only the first two harmonics are shown. The first and second harmonics contributed to most of the explained variance of the mean T_{BB} at all data rings (0.41–0.76 for hurricanes, 0.61–0.93 for tropical storms). A plot of the first and second harmonics of the 24 h time series is shown in Figs. 4 and 5. Other harmonics (particularly 3, 4, 5 and 6) contribute noticeably (0.16–0.38) to the total variance outward to 277.5 km. Beyond this distance, the contribution from these latter harmonics weakens. A one-sided Fisher *t* test shows that the first harmonic is statistically significant at the 0.0005 level at most data rings. The second harmonic is statistically significant at the 0.01 level but only in tropical storms from 610.5 km radius outward and at a radius of 166.5 km.

The time of day of the maxima (minima) of the harmonics varies with distance, but three distinct patterns are present (positive amplitudes are associated with higher mean T_{BB}, or cloud minima; negative amplitudes are associated with lower mean T_{BB}, or cloud maxima). The pattern (first harmonic) in the outer environment (499.5–832.5 km radii) of the

TABLE 1. Statistics of the Fourier analysis of the 24 h time series of the mean T_{BB} of Atlantic Ocean tropical storms.

	Data ring							
	1	2	3	4	5	6	7	8
Nominal radius from center (km)	55.5	166.5	277.5	388.5	499.5	610.5	721.5	832.5
Grand mean T_{BB}	221.5	240.7	257.0	268.4	275.0	279.6	282.0	283.2
Standard deviation of grand mean T_{BB}	2.28	2.07	2.36	3.13	2.74	2.46	2.28	2.02
Harmonic 1								
Maximum amplitude	2.72	1.83	2.66	3.97	3.42	2.79	2.71	2.29
Standard deviation	1.92	1.30	1.88	2.81	2.42	1.97	1.91	2.02
†Time from origin (LST)	1937	2125	2357	0217	0358	0436	0517	0535
Explained variance	0.72	0.39	0.64	0.81	0.78	0.65	0.70	0.65
t statistic	7.39**	3.76**	6.24**	9.42**	8.77**	6.32**	7.21**	6.35**
Harmonic 2								
Maximum amplitude	0.60	1.40	1.14	1.39	1.38	1.78	1.54	1.51
Standard deviation	0.44	0.99	0.80	0.99	0.98	1.26	1.09	1.07
Time from origin (LST)†	0857	1008	1101	1220	1148	1157	0005	0005
Explained variance	0.04	0.22	0.12	0.10	0.13	0.26	0.23	0.28
t statistic	0.92	2.54*	1.70	1.55	1.79	2.79*	2.54*	2.93*

* Significant at 0.01 level.
** Significant at 0.0005 level.
† Time from origin is given in hours and minutes after 0000 LST.

tropical cyclones (both intensity categories) exhibits a cloud maximum (minimum) at ~1700 (~0500) LST. Cloud maximum or minimum implies increased or decreased areal coverage and cloud top height. This cycle is in phase with the areal distribution of three T_{BB} thresholds (223, 239, 253 K) of Atlantic Ocean tropical cyclones reported by Browner *et al.* (1977). A second pattern (first harmonic) at the inner

TABLE 2. Statistics of the Fourier analysis of the 24 h time series of the mean T_{BB} of Atlantic Ocean hurricanes.

	Data ring							
	1	2	3	4	5	6	7	8
Nominal radius from center (km)	55.5	166.5	277.5	388.5	499.5	610.5	721.5	832.5
Grand mean T_{BB} (K)	214.1	232.0	251.8	265.2	272.6	276.8	279.0	280.1
Standard deviation of grand mean T_{BB}	1.42	1.93	2.50	2.09	1.40	1.10	1.02	0.82
Harmonic 1								
Maximum amplitude	1.01	1.38	2.93	2.16	1.40	1.19	1.19	0.80
Standard deviation	0.72	0.98	2.07	1.53	0.99	0.84	0.84	0.56
†Time from origin (LST)	1308	0437	0403	0427	0420	0613	0540	0732
Explained variance	0.25	0.26	0.69	0.54	0.50	0.59	0.69	0.48
t statistic	2.73*	2.76*	7.01**	5.03**	4.66**	5.59**	6.69**	4.49**
Harmonic 2								
Maximum amplitude	0.92	1.05	0.92	1.23	0.46	0.46	0.30	0.33
Standard deviation	0.65	0.74	0.65	0.87	0.33	0.35	0.21	0.23
Time from origin (LST)†	0758	0747	0437	0445	0404	0525	0544	0526
Explained variance	0.21	0.15	0.07	0.17	0.06	0.09	0.04	0.08
t statistic	2.40	1.95	1.27	2.14	1.13	1.45	1.00	1.39

* Significant at 0.01 level.
** Significant at 0.0005 level.
† Time from origin is given in hours and minutes after 0000 LST.

core (55.5 km radius) differs in time from that at the outer environment. A cloud maximum (minimum) occurs near 0100 (1300) LST in hurricanes and near 0800 (2000) LST in tropical storms. Although there is a temporal difference of 6.5 h between the time of cloud maximum (minimum) of the two intensity categories, this deep convection cycle compares favorably with the cycle of deep cumulus convection found to occur at small islands in the western Pacific Ocean by Gray and Jacobson (1977) and also with the radiational forcing mechanism they postulated. The deep convection cycle is also in phase with that found with the coldest region of clouds ($T_{BB} \leqslant 203$ K) of mature Pacific Ocean typhoons by Muramatsu (1983). A third pattern (first harmonic) between the inner core and the outer environment shows a temporal progression of the cloud maximum (minimum) with distance. The progression is at a rate of 53 km h^{-1} and appears only in the tropical storm time series. This pattern agrees with a similar progression found to be associated with increasing T_{BB} thresholds in Pacific Ocean typhoons (Muramatsu, 1983), the outward advection of cirrus generated at the eyewall (Merritt and Wexler, 1967), the postulation of spreading debris from early morning convection (Browner *et al.*, 1977) and the lag of cloud maxima (minima) at increasing T_{BB} thresholds for Atlantic and Pacific Ocean tropical cyclones (Dvorak, personal communication, 1983).

The second harmonic is most statistically significant at the outer environment (610.5–832.5 km radii) of the tropical storm time series. The time of the cloud maxima (0600 and 1800 LST) and minima (0000 and 1200 LST) agree well with the cloud cycle postulated by the semidiurnal pressure wave (S_2 oscillation) (Brier and Simpson, 1969). The pressure wave oscillation would enhance convection during periods of pressure rise (0700 and 1900 LST) and inhibit convection during periods of pressure fall (0100 and 1300 LST).

The significance of the second harmonic at other regions of the tropical cyclones is weak; yet, it is more often statistically significant at a higher level than the succeeding harmonics.

4. Conclusions

The geostationary T_{BB} measurements have provided new information that shows that the mean top of the dense cloud canopy of hurricanes is near 10.6 km and extends horizontally to near 321 km. In tropical storms the mean top of the dense canopy is near 9.7 km and extends horizontally to near 278 km. The deep convection near the center of hurricanes is more widespread and more intense than in tropical storms.

Highly significant diurnal and semidiurnal cloud cycles are found to exist. In the outer periphery of the tropical cyclones a diurnal cloud maximum (minimum) is found to occur near 1700 (0500) LST. Near the storm center where deep convection exists, the diurnal convective maximum (minimum) is found to occur near 0100 (1300) LST in hurricanes and near 0800 (2000) LST in tropical storms. A diurnal temporal progression of the cloud maximum (minimum) takes place between the inner core convection and the outer periphery of tropical storms. Semidiurnal cloud maxima (minima) are found to occur near 0600 and 1800 (0000 and 1200) LST in the outer periphery of tropical storms. These cycles are in harmony with the results of other investigations. The cycles appear to be the response of cloud and convective activity to postulated radiational and solar–lunar tidal forcing mechanisms.

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REFERENCES

Adler, R. F., and D. D. Fenn, 1979: Thunderstorm intensity as determined from satellite data. *J. Appl. Meteor.*, **18,** 502–517.

Brier, G. W., and J. Simpson, 1969: Tropical cloudiness and precipitation related to pressure and tidal variations. *Quart. J. Roy. Meteor. Soc.*, **95,** 120–147.

Browner, S., W. L. Woodley and C. G. Griffith, 1977: Diurnal oscillation of the area of cloudiness associated with tropical storms. *Mon. Wea. Rev.*, **105,** 856–864.

Gentry, R. C., E. Rodgers, J. Steranka and W. Shenk, 1980: Predicting tropical cyclone intensity using satellite measured equivalent blackbody temperature of cloud tops. *Mon. Wea. Rev.*, **108,** 445–455.

Gray, W. M., and R. W. Jacobson, Jr., 1977: Diurnal variation of deep cumulus convection. *Mon. Wea. Rev.*, **105,** 1171–1188.

Heymsfield, G. M., G. Szejwach, S. Schotz and R. H. Blackmer, Jr., 1983: Upper-level structure of Oklahoma tornadic storms on 2 May 1979. Part II: Proposed explanation of "V" pattern and internal warm region in infrared observations. *J. Atmos. Sci.*, **40,** 1756–1767.

Merritt, E. S., and R. Wexler, 1967: Cirrus canopies in tropical storms. *Mon. Wea. Rev.*, **95,** 111–120.

Muramatsu, T., 1983: Diurnal variations of satellite-measured T_{BB} areal distribution and eye diameter of mature typhoons. *J. Meteor. Soc. Japan,* **61,** 77–90.

Panofsky, H. A., and G. W. Brier, 1965: *Some Applications of Statistics to Meteorology.* The Pennsylvania State University, 224 pp.

Riehl, H., 1954: *Tropical Meteorology.* McGraw-Hill, 392 pp.